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Fabrication and testing of a non-glass vacuum-tube collector for solar energy utilization

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ABSTRACT

An evacuated tubular solar collector was fabricated from acrylics for improved resistance to shattering. A plasmatron was employed to apply a thin gas-barrier coating to the surfaces of the plastic tube to prevent/alleviate gas infiltration. Experiments were conducted to investigate the effect of vacuum level on the performance of the non-glass vacuum-tube solar collector. Inserted in the evacuated tube was a finned heat pipe for solar energy collection and heat transfer to a water tank. Time variations of temperatures on the heat pipe surface and in the water tank were recorded and analyzed for different degrees of vacuum in the collector. The steady-state temperature of the non-glass collector was compared to that of a commercial glass vacuum-tube collector to assess the feasibility of the use of evacuated plastic tubes for solar energy collection. A simple analytical model was also developed to assist in understanding and analyzing the transient behavior and heat losses of the vacuum-tube solar collector.

1. Introduction

With the official effectuation of the Kyoto Protocol in 2005, most countries today have to assume the duty of reducing greenhouse gas emissions. This global agreement and recent wildly fluctuating oil prices have boosted the use of renewable energy for sustainable development. Compared to other renewable energy, solar energy is very reliable and cost-effective, and there is a long history of solar energy utilization dating back to Greeks' design of solar architecture and ancient solar agricultural applications.

Among the various solar energy applications, solar water heating (SWH) is probably the simplest and most prevalent method of harnessing the sun's energy. The collector is the key component of a SWH system. Flat-plate collectors were the most common collector design for SWH prior to the arrival of vacuum-tube collectors. Vacuum-tube collectors, which have been studied somewhat extensively in the past [e.g., Refs. [1–8]], can achieve fairly high temperatures, thus have higher heat transfer rates and work potentials and can be used for solar-cooling and power-generation applications.

Two types of vacuum-tube collectors have been developed for SWH: single-tube and double-tube. The former involves a flat or curved metal stripe attached or soldered to a heat pipe or water pipe in an evacuated glass tube. The latter consists of two concentric cylindrical glass tubes. The inner tube is coated with an absorptive coating. The jacket between the two glass tubes is evacuated to reduce heat loss.

One major drawback of glass-tube collectors is that glass breaks easily. The inherent weakness of glass material makes it expensive to fabricate and ship vacuum-tube solar collectors. To alleviate this problem the authors and a few other researchers (e.g., Ref. [6]) have developed non-glass solar collectors for improved shattering resistance. Presented in this paper are preliminary results of the heat transfer experiment of the authors' vacuum-tube collector fabricated from acrylics. The relationship between the vacuum level inside the non-glass tubular collector and the behavior and performance of the collector were investigated.

2. Experimental apparatus and procedure

Plastics such as acrylics are highly transparent to solar flux and have much better resistance to shattering than glass. The vacuum-tube solar collector investigated in this paper was composed of an acrylic tube and a finned heat pipe, as shown in Fig. 1. The acrylic tube was selected due to its low price and commercial availability. The tube was 450 mm long, 70 mm in diameter, with a wall thickness of 10 mm. The two ends of the tube were sealed with acrylic caps and copper adapters.

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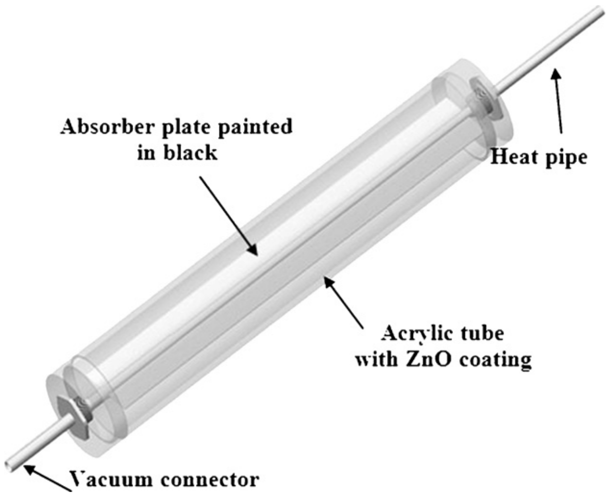

Fig. 1. Non-glass solar collector.

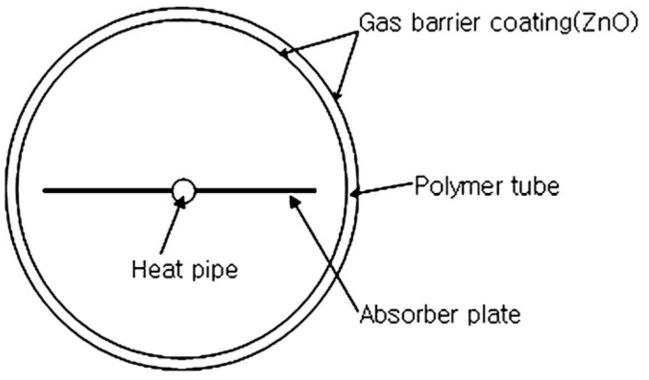

Fig. 2. Cross-sectional view of the tubular collector. Dimensions and property values are listed in Table 1.

The performance of the heat pipe has a profound effect on radiation energy collection and transfer. The heat pipe in the present investigation was made from a thin-walled copper tube, 550 mm long, 8 mm in outer diameter, with ethyl alcohol as the working fluid. A thin copper sheet, 380 mm by 56 mm, was attached to the copper tube to increase the surface area for radiation absorption as depicted in Fig. 2. The surface of the absorber plate and the copper tube surface facing the radiation source were treated with a selective black coating called Thurmalox-250. Thurmalox-250 is a silicone-based heat resistant coating (by Dampney Co., Inc.) designed for use on metal surfaces of solar collectors [9]. Its absorptivity and emissivity are 0.96 and 0.65, respectively. The cold end of the heat pipe protruded out of the top plastic cap and was immersed in an insulated water tank of 1-liter capacity. A vacuum connector was connected to the bottom of the tubular collector for evacuating gases in the collector. Physical properties and dimensions of the major components of the experimental set-up can be found in Table 1.

The hurdles and difficulties to overcome when plastic tubes are used for solar energy collection were discussed in Ref. [10]. Unlike glass and quartz that are perfectly airtight, air infiltration takes place through tiny pores in plastics. The infiltration rate depends on the texture and thickness of the plastics and the pressure difference. In addition, gases initially contained in plastics may be released when the ambient pressure drops considerably. These effects make it difficult to maintain a high degree of vacuum in a plastic tube.

A main objective of the present investigation is to develop a way to alleviate air infiltration and release of contained gases of the acrylic tube. The method we adopted was to spray the acrylic tube surfaces with a gas-barrier coating to prevent or slow down gas leakage into the evacuated tube. Shown in Fig. 3 is the set-up for coating a thin layer of ZnO on the acrylic tube inner and outer surfaces using a plasmatron. The change in solar transmittance due to the ZnO coating can be seen in Fig. 4. The bare acrylic tube has a transmittance almost identical to that of glass. The coated tube has a slightly lower transmittance due to the radiation absorbed by the ZnO coating. The transmittance of the coating applied to the tube surfaces in a vacuum environment (case c in Fig. 4) was found to be slightly higher than that at the atmospheric pressure (case b). As for the lifetime of the applied gas-barrier coating, ZnO behaves as a ceramic material and has a very long lifetime. It has been used as a conductive film in thin-film solar cells which typically have a lifetime of more than 20 years.

During the experiments the tube was connected to a header-type vacuum chamber equipped with pressure monitoring and controlling devices and a vacuum pump. The pressure inside the acrylic tube was monitored by a vacuum gauge. LabVIEW was used to save and analyze the experimental data in a real-time mode.

A solar simulator consisting of 20 halogen lamps (maximum power = 75 W each) was used in our experiments to generate a heat flux of 800 W/m^2 on the absorber plate with a mean error of ±25 W/m^2. Four K-type thermocouples were attached to the back of the absorber plate, and the fifth thermocouple was placed in the gap between the back of the absorber plate and the acrylic tube, as shown in Fig. 5. The uncertainties associated with these measurements are ±1.5 °C. A data acquisition system by AGILENT was used for temperature measurements. Temperature variations were measured over a 10 h period for two levels of vacuum, 0.01 and 5 torr, in the tube.

Due to the low-cost vacuum chamber we built and the air infiltration and gas-releasing problems, the highest vacuum level our experimental apparatus can reach was about 0.01 torr. During

Table 1
Property values and component dimensions used in the analytical model.

Finned heat pipe	Copper tube: inner and outer diameters: 6 and 8 mm; length: 550 mm Length of copper tube immersed in the water tank: $L_{t,\ inside}$: 117 mm Copper sheet: 380 × 56 × 0.5 mm Black paint: absorptivity (α): 0.96 Emissivities of coated and uncoated surfaces: $\epsilon_1 = 0.65$; $\epsilon_2 = 0.265$ Copper density: 8933 kg/m^3 Copper specific heat: 385 W/kg °C
Acrylic tube	Inner and outer diameters: 60 and 70 mm; mass = 0.506 + 2(caps) *0.115 = 0.736 kg Transmissivity (τ): 0.9 Thermal conductivity: 0.19 W/m °C Specific heat: 1450 W/kg °C
Insulated water tank	PVC pipe: outer diameter: 114 mm; length: 350 mm; mass: 0.57 kg; specific heat: 1100 W/kg °C Polyethylene foam: thickness: 4 mm; thermal conductivity: 0.036 W/m °C Water in the tank: volume: 1 l; density: 997 kg/m^3; thermal conductivity: 0.613 W/m °C; expansion coefficient: 276×10^{-6} K^{-1}; thermal diffusivity: 1.471×10^{-7} m^2/s; kinematic viscosity: 8.58×10^{-7} m^2/s; specific heat: 4179 W/kg °C
Air	In the acrylic tube: thermal conductivity: 0.0263 W/m °C Outside the collector: thermal conductivity: 0.0263 W/m °C; expansion coefficient: $1/[(T_a + T_{p\ or\ insulation})/2]$ K^{-1}; thermal diffusivity: 22.5×10^{-6} m^2/s; kinematic viscosity: 15.9×10^{-6} m^2/s